Concurrently Verifying and Validating the Critical Path and Margin Allocation Using Probabilistic Analysis

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PROBLEM STATEMENT

While government and industry space communities generally use scheduling software tools that can automatically calculate the critical path in large, complex schedules, the deterministic critical path is not necessarily the path most likely to drive schedule completion. Uncertainty and risk impacts to tasks need to be considered. Performing a probabilistic schedule risk analysis that takes into account the uncertainty and discrete risks associated with technical activities should help the project to identify its most likely critical path.

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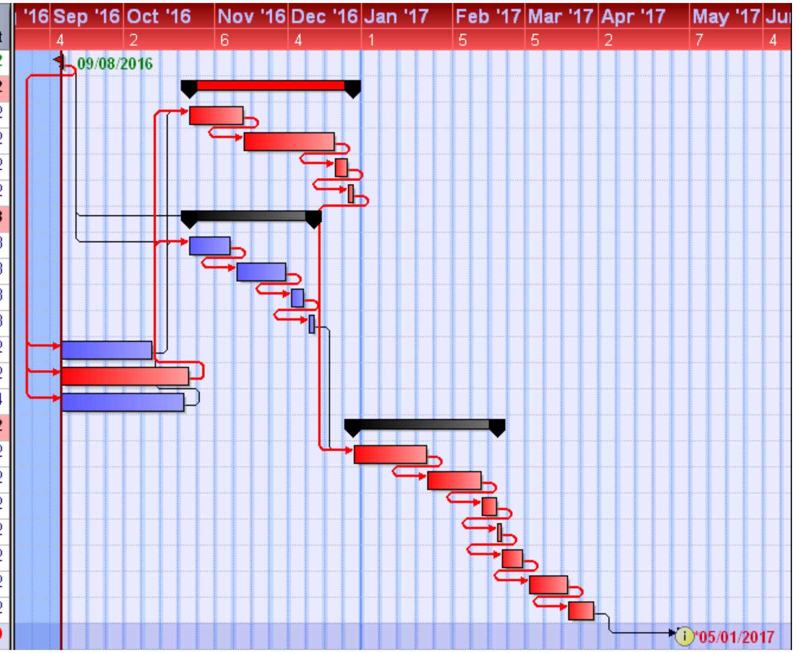
ID	Description	Remaining Duration	Start	Finish	Preceding Tasks	Succeeding Tasks	Total Finish Float
000001	Aurora Mission	0	09/08/2016			0010;000013;000	22
000002	Instrument 1	45	10/27/2016	12/28/2016			22
000003	Design 1	15	10/27/2016	11/16/2016	0010;000013;00001	000004	22
000004	Build 1	25	11/17/2016	12/21/2016	000003	000005	22
000005	Test 1	3	12/22/2016	12/26/2016	000004	000006	22
000006	Pack andShip 1	2	12/27/2016	12/28/2016	000005	000015	22
000007	Instrument 2	34	10/27/2016	12/13/2016	000001		33
000008	Design 2	12	10/27/2016	11/11/2016	0010;000013;00001	000009	33
000009	Build 2	15	11/14/2016	12/02/2016	000008	000010	33
000010	Test 2	5	12/05/2016	12/09/2016	000009	000011	33
000011	Pack and Ship 2	2	12/12/2016	12/13/2016	000010	000015	33
000012	Subsystem Development 1	25	09/08/2016	10/12/2016	000001	000003;000008	32
000013	Subsystem Development 2	35	09/08/2016	10/26/2016	000001	000003;000008	22
0010	Subsystem Development 3	33	09/08/2016	10/24/2016	000001	000003;000008	24
000014	System Integration Final Testing	39	12/29/2016	02/21/2017			22
000015	Integrate Systems	20	12/29/2016	01/25/2017	000011;000006	000016	22
000016	Test System	15	01/26/2017	02/15/2017	000015	000017	22
000017	Ship to Launch Site	4	02/16/2017	02/21/2017	000016	000018	22
000018	Facility Checks	2	02/22/2017	02/23/2017	000017	000019	22
000019	Final Alignment	6	02/24/2017	03/03/2017	000018	000020	22
000020	Launch Vehicle Integration and En...	11	03/06/2017	03/20/2017	000019	000021	22
000021	Launch Activities	8	03/21/2017	03/30/2017	000020	000023	22
000023	Launch	0		*05/01/2017	000021		0



EXAMINING THE *CRITICAL PATH*

Critical Path Definition – The critical path is the sequence of tasks or activities that typically represents the longest path through a project, which determines the shortest possible project duration (i.e., lowest total float).

Critical Path – The Simple Facts

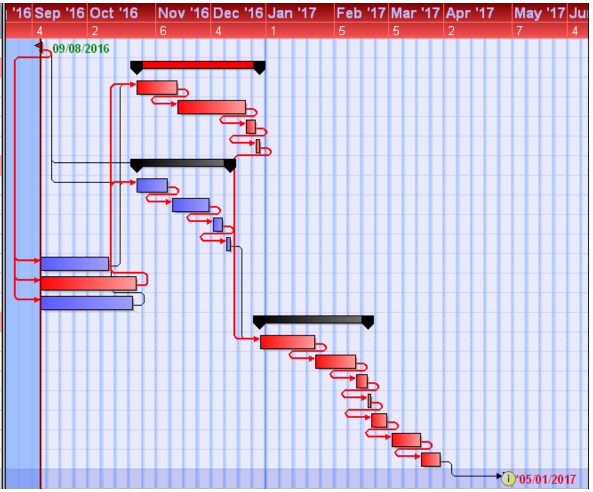
- **Common characteristics of a credible critical path include the following**
  - it typically begins at "time now" and proceeds to project completion (or a key end item…*we'll get back to this*)
  - the tasks and milestones are tied together with network logic in a sequence that is programmatically feasible or otherwise makes sense from a workflow standpoint
  - there are no gaps in time between tasks that cannot be explained
- **To guarantee that the critical path is being calculated correctly, the IMS must:**
  - capture all the project's activities
  - be logically linked without the presence of dangling tasks
  - be free from inappropriate date constraints
  - have level of effort tasks clearly marked (or modeled as hammock tasks) to prevent them from influencing the criticality of the work flow

Clarification Point: Sometimes constraints make sense…and sometimes they don't.
Hard constraints are seldom justified, whereas soft constraints might be. While avoiding the use of constraints altogether is ideal for critical path calculations, there are some instances where spaceflight projects need to incorporate project-specific constraints, such as **procurement starts**, **deliveries from partner organizations**, or **in cases where funding needs to be made available before work can begin**.

Critical Path – More Simple Facts

- **The *critical path* of interest may be tied to something other than the project end date, such as a key end item or delivery.**
  - Examples of key end items or deliveries might be "spacecraft delivery" or "launch", even though the project schedule may continue through operations and sustainment.
  - A project should determine what milestone or key end item, along the critical path, it plans to manage to, so that it can properly identify and proactively manage the activities along its critical paths.
- Any activity on the critical path is called a ***critical path activity***.

ID	Description	Remaining Duration	Start	Finish	Preceding Tasks	Succeeding Tasks	Total Finish Float
000001	Aurora Mission	0	09/08/2016			0010;000013;000	22
000002	Instrument 1	45	10/27/2016	12/28/2016			22
000003	Design 1	15	10/27/2016	11/16/2016	0010;000013;00001	000004	22
000004	Build 1	25	11/17/2016	12/21/2016	000003	000005	22
000005	Test 1	3	12/22/2016	12/26/2016	000004	000006	22
000006	Pack andShip 1	2	12/27/2016	12/28/2016	000005	000015	22
000007	Instrument 2	34	10/27/2016	12/13/2016	000001		33
000008	Design 2	12	10/27/2016	11/11/2016	0010;000013;00001	000009	33
000009	Build 2	15	11/14/2016	12/02/2016	000008	000010	33
000010	Test 2	5	12/05/2016	12/09/2016	000009	000011	33
000011	Pack and Ship 2	2	12/12/2016	12/13/2016	000010	000015	33
000012	Subsystem Development 1	25	09/08/2016	10/12/2016	000001	000003;000008	32
000013	Subsystem Development 2	35	09/08/2016	10/26/2016	000001	000003;000008	22
0010	Subsystem Development 3	33	09/08/2016	10/24/2016	000001	000003;000008	24
000014	System Integration Final Testing	39	12/29/2016	02/21/2017			22
000015	Integrate Systems	20	12/29/2016	01/25/2017	000011;000006	000016	22
000016	Test System	15	01/26/2017	02/15/2017	000015	000017	22
000017	Ship to Launch Site	4	02/16/2017	02/21/2017	000016	000018	22
000018	Facility Checks	2	02/22/2017	02/23/2017	000017	000019	22
000019	Final Alignment	6	02/24/2017	03/03/2017	000018	000020	22
000020	Launch Vehicle Integration and En...	11	03/06/2017	03/20/2017	000019	000021	22
000021	Launch Activities	8	03/21/2017	03/30/2017	000020	000023	22
000023	Launch	0		*05/01/2017	000021		0



The critical path is highlighted in *red* in the schedule (figure) to the left. Each red activity is a ***critical path activity***.

Critical Path – The Complicated Facts

- ***Critical Path Activities* vs *Critical Activities* –** It is extremely important to note the difference between critical path activities and critical activities as defined by management.
  - These terms may be synonymous, but that is not always the case.
  - Critical activities may be defined as any tasks (or milestones) which have been deemed important enough to have this distinction assigned to them, but may or may not show up on the critical path.
  - Examples of critical activities:
    - Key decision points
    - Development of a primary system component
    - Important tests
    - Other high-risk technical activities that are deemed "critical"

Clarification Point: Do we need to track both the critical path and critical activities?
Project Management may be more interested in tracking the "critical activities" rather than the critical path activities. Is this a problem? Maybe, maybe not…but how do we know?

Critical Path and *Float*

- **The critical path is defined by float –** it is typically characterized as the path in the scheduled with the least amount of ***total float*.**
- **What is float?**
  - **Float** (or slack) is the amount of time that a task can be delayed without causing a delay to subsequent tasks ("free float") or to the project/end item completion date ("total float").
  - Float can be used to absorb performance delays, as well as uncertainties and risks.
- **What does float really tell us…and why do we care?**
  - On any path, the ***schedule flexibility*** is measured by the amount of time that a schedule activity can be delayed or extended from its early start date without delaying the project finish date or violating a schedule constraint, and is termed "total float."
  - Calculating the float in the schedule is particularly important for the space community because spaceflight missions are often constrained by launch dates, which limits the amount of available time in the schedule and makes the flexibility to revise various workflows more important with respect to managing risks.

Critical Path and *Margin*

- **What is margin?**
  - **Schedule margin** is a separately planned quantity of time above the planned duration estimate reflected in the baselined schedule.
  - The purpose of schedule margin is to account for uncertainty and risks, whether it be to mitigate or "buy-down" the risks or to absorb the impact of schedule uncertainty and/or realized risks.
  - Schedule margin durations should not be used to hold a deliverable forecast to a static date, but should be based upon risks and uncertainties.
- **Why do we care?**
  - Adequate schedule margin appropriately placed in a project schedule is critical to project success.
  - Management should determine an adequate amount of schedule margin to be included in the schedule before baselining.
- **How can we effectively establish and use margin?**
  - *We'll get to that in a minute…*

DETERMINISTIC SCHEDULES – W/MARGIN AND W/O MARGIN

Deterministic schedules are networks of tasks connected to each other with dependencies that describe the work to be performed, that work's duration and the planned completion of the project.

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Identifying the Deterministic Critical Path pre-Margin

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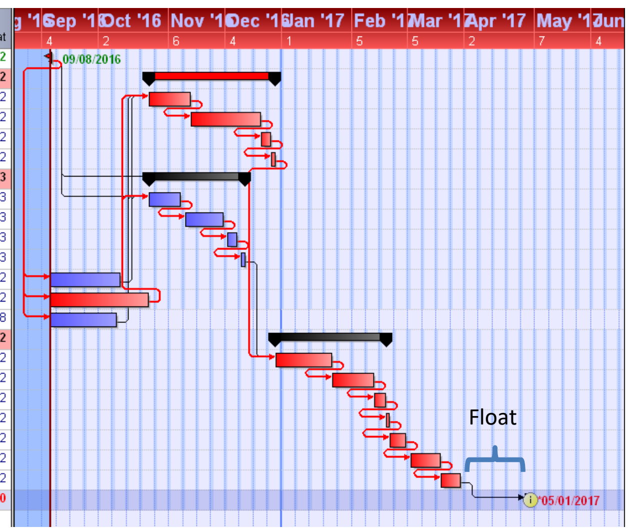
- This ***pre-margin deterministic critical path*** example assumes that float may exist between the finish date of the last activity/planned date and the finish milestone/committed date.
- If the deterministic critical path in this scenario contained zero (0) float to the project end item date, there would be no room to incorporate margin tasks to manage uncertainties and mitigate risks.

ID	Description	Remaining Duration	Start	Finish	Preceding Tasks	Succeeding Tasks	Total Finish Float
000001	Aurora Mission	0	09/08/2016			0010;000013;00001	22
000002	Instrument 1	45	10/27/2016	12/28/2016			22
000003	Design 1	15	10/27/2016	11/16/2016	0010;000013;000012	000004	22
000004	Build 1	25	11/17/2016	12/21/2016	000003	000005	22
000005	Test 1	3	12/22/2016	12/26/2016	000004	000006	22
000006	Pack andShip 1	2	12/27/2016	12/28/2016	000005	000015	22
000007	Instrument 2	34	10/27/2016	12/13/2016	000001		33
000008	Design 2	12	10/27/2016	11/11/2016	0010;000013;000012;	000009	33
000009	Build 2	15	11/14/2016	12/02/2016	000008	000010	33
000010	Test 2	5	12/05/2016	12/09/2016	000009	000011	33
000011	Pack and Ship 2	2	12/12/2016	12/13/2016	000010	000015	33
000012	Subsystem Development 1	25	09/08/2016	10/12/2016	000001	000003;000008	32
000013	Subsystem Development 2	35	09/08/2016	10/26/2016	000001	000003;000008	22
0010	Subsystem Development 3	33	09/08/2016	10/10/2016	000001	000003;000008	48
000014	System Integration Final Testing	39	12/29/2016	02/21/2017			22
000015	Integrate Systems	20	12/29/2016	01/25/2017	000011;000006	000016	22
000016	Test System	15	01/26/2017	02/15/2017	000015	000017	22
000017	Ship to Launch Site	4	02/16/2017	02/21/2017	000016	000018	22
000018	Facility Checks	2	02/22/2017	02/23/2017	000017	000019	22
000019	Final Alignment	6	02/24/2017	03/03/2017	000018	000020	22
000020	Launch Vehicle Integration and En...	11	03/06/2017	03/20/2017	000019	000021	22
000021	Launch Activities	8	03/21/2017	03/30/2017	000020	000023	22
000023	Launch	0		*05/01/2017	000021		0



The last activity on the critical path, Launch Activities, has a 03/30/17 finish date; however, the finish milestone, Launch, is not scheduled to occur until 05/01/17. Thus, there are 22 days of total float on the activities in the critical path, which in this case, is the longest path in the schedule (but not a zero-float path).

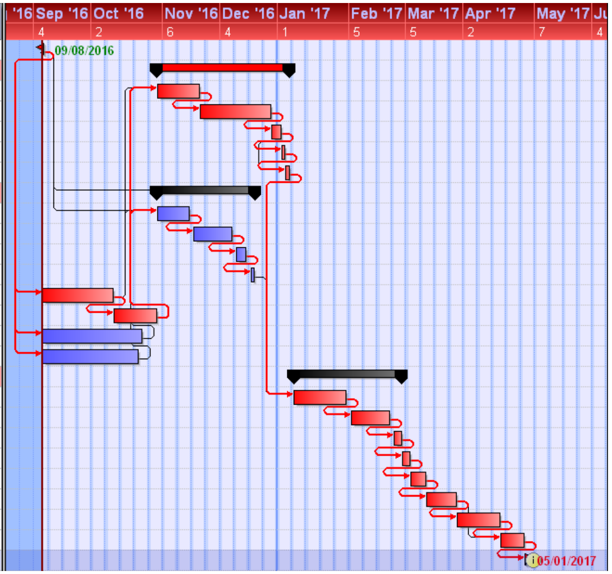
Identifying the Deterministic Critical Path post-Margin

- **When margin is allocated** to the schedule, **there may be some small amount of float** remaining on the critical path that has not been *replaced* by the margin activity, **or there may be zero float.**

- The post-margin CP may not be the same as the pre-margin CP.

- This ***post-margin deterministic critical path*** example assumes that margin has been allocated to the schedule (through whatever means – SRA, management preference, etc.), such that there is zero float remaining on the critical path.

ID	Description	Remaining Duration	Start	Finish	Preceding Tasks	Succeeding Tasks	Total Finish Float
000001	**Aurora Mission**	0	09/08/2016			0010;000013;00(	0
000002	**Instrument 1**	**47**	**11/03/2016**	**01/06/2017**			**0**
000003	Design 1	15	11/03/2016	11/23/2016	0010;0030;000013;0	000004	0
000004	Build 1	25	11/24/2016	12/28/2016	000003	000005	0
000005	Test 1	3	12/29/2016	01/02/2017	000004	0020;000006	0
0020	Margin - Test 1 (2 days)	2	01/03/2017	01/04/2017	000005	000006	0
000006	Pack andShip 1	2	01/05/2017	01/06/2017	0020;000005	000015	0
000007	**Instrument 2**	**34**	**11/03/2016**	**12/20/2016**	**000001**		**13**
000008	Design 2	12	11/03/2016	11/18/2016	0010;0030;000013;0	000009	13
000009	Build 2	15	11/21/2016	12/09/2016	000008	000010	13
000010	Test 2	5	12/12/2016	12/16/2016	000009	000011	13
000011	Pack and Ship 2	2	12/19/2016	12/20/2016	000010	000015	13
000012	Subsystem Development 1	25	09/08/2016	10/12/2016	000001	0030;000003;00(	0
0030	Margin - Subsystem 1 (15 days)	15	10/13/2016	11/02/2016	000012	000003;000008	0
000013	Subsystem Development 2	35	09/08/2016	10/26/2016	000001	000003;000008	5
0010	Subsystem Development 3	33	09/08/2016	10/24/2016	000001	000003;000008	7
000014	**System Integration Final Testing**	**39**	**01/09/2017**	**03/02/2017**			**0**
000015	Integrate Systems	20	01/09/2017	02/03/2017	000011;000006	000016	0
000016	Test System	15	02/06/2017	02/24/2017	000015	000017	0
000017	Ship to Launch Site	4	02/27/2017	03/02/2017	000016	000018	0
000018	Facility Checks	2	03/03/2017	03/06/2017	000017	000019	0
000019	Final Alignment	6	03/07/2017	03/14/2017	000018	000020	0
000020	Launch Vehicle Integration and Encaps...	11	03/15/2017	03/29/2017	000019	0040;000021	0
0040	Margin - Pre-Launch Activities (15 days)	15	03/30/2017	04/19/2017	000020	000021	0
000021	Launch Activities	8	04/20/2017	05/01/2017	0040;000020	000023	0
000023	**Launch**	**0**		**05/01/2017**	**000021**		**0**



The addition of margin entry ***Margin–Sub1*** *changed the schedule's critical path.* ***How do we know if the margin placement makes sense?*** *Project management should be aware of the deterministic critical path prior to margin placement and have rationale for the allocation of all margin. That rationale* ***may*** *be based on an SRA.*

PROBABILISTIC SCHEDULES – W/UNCERTAINTY & RISKS, BUT W/O MARGIN

Probabilistic schedules are schedule logic networks with all the elements of a deterministic plan, but the plan is risk informed, such that discrete risks are mapped to the schedule and durations of the tasks are random variables.

What it Means to Have a Risk-Informed Schedule

- **NASA policy states** that a **project schedules should be *risk-informed*** at various levels throughout the project life cycle.
  - NPR 7120.5 defines risk as "the potential for performance shortfalls, which may be realized in the future, with respect to achieving explicitly established and stated performance requirements."
  - Risk impacts affecting any of the critical or near-critical paths may cause the schedule completion date to slip. It is important to understand what is driving each of these paths, and which path is the most likely to be critical.
- **Typically, from a risk management perspective, discrete risks are identified, tracked, and mitigation plans are formulated.**
- **By *risk-informed*, the policy is stating that all appropriate discrete risks be considered in the project schedule, *but* it is also the intent of the policy for risk-informed to account for various uncertainties (that may not be discretely managed in the risk management system – including estimate accuracy of task durations).**

SRAs – Importance to Stakeholders

- **Project Schedulers/Schedule Analysts**
  - SRAs verify the project plan
    - Ensures that the true critical path can be identified and communicated
    - Facilitates the integration of PP&C functions (and programmatic products)
    - Helps with the understanding, characterization, and quantification risks that have schedule impacts
    - Allows for sensitivity analysis/trade studies of schedule activity sequencing and/or risk reduction activities
- **NASA Project Managers**
  - SRAs provide a way to integrate programmatic information to communicate to Agency decision makers about achievability of schedule with given risks and reserves
    - Aids in the prioritization of risks
    - Illustrates the differences between "important" activities and critical path activities; identifies the most likely critical path(s). (Note: At any point in time, the critical path *may* or *may not* contain activities that management believes are particularly important.)
    - Identifies flexibility in the schedule
    - Determines adequacy of margin allocation (how much and location)
    - Provides a basis for implementing risk mitigations
    - Establishes confidence levels from which the project can validate their baseline
- **Independent Assessors**
  - SRAs provide an examination of the credibility and confidence of the project plan
    - Justifies the project's basis for activity durations, as well as risk likelihoods and impacts
    - Verifies the realism of the project's plan
    - Provides assurance of the project's risk posture

Modeling the Probabilistic Schedule

- **Perform a Schedule Health Check and Schedule Analysis on the IMS (or analysis schedule)**
  - Address any issues in the Health Check; Perform a Critical Path Test
  - Understand the deterministic schedule and critical path(s)
  - *If later in the life cycle*, analyze performance trends/metrics to aid in understanding uncertainty
- **Define Duration Uncertainty Methods/Distributions**
- **Quantify Risks - Likelihood (Probability) & Impact (Duration Distribution)**
- **Build a Schedule Risk Analysis (SRA) model in a schedule risk analysis tool (JACS, Polaris, etc.)**
  - Import the IMS (or analysis schedule) into the SRA tool
  - Assign uncertainty to tasks (e.g., three-point estimates)
  - Map discrete risks to tasks in the schedule/model
- **Run Simulation and Analyze Results**
  - Probabilistic Critical Path
  - Risk Prioritization (e.g., Tornado Charts, Ruhm-Mango-Kreps Algorithm)
- **Perform Trade Studies / Sensitivity Analysis**
  - Understand the sensitivity of the uncertainty distributions applied
  - Understand the risk prioritization and how it changes as the risk profile changes

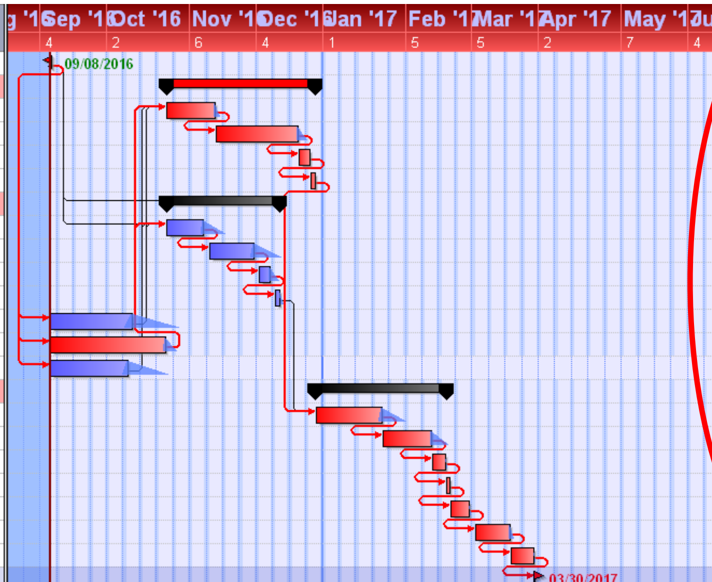
Schedule Uncertainty

- **All planned durations have some uncertainty**
- **Process is to break schedule uncertainty bounds into two factors**
  - Risks via the Risk Register (MAJOR FOCUS) – *these are discrete risks, "known unknowns"*
  - General uncertainty in the baseline plan (i.e. activity durations) – *this is uncertainty, "unknown unknowns"*
- **Uncertainty can be approached by understanding:**
  - Complexity of the work
  - Underlying slack assumptions
  - Confidence in meeting plan (e.g., optimistic vs pessimistic bias)
- **There are three suggested methods for selecting schedule uncertainty distributions:** ***data driven*** (parametric estimates, etc.), ***performance based*** (earned value metrics, earned schedule metrics, etc.), and ***subject matter expert*** approaches
- **Activities deemed "critical" by management should be carefully considered when applying uncertainty**

Applying Uncertainty

- **Uncertainty can be applied at the *summary level* or at a *task level***
  - ***Summary Level*** is a bit of a misnomer. Schedule risk analysis software typically requires that uncertainty be applied on a task (versus a summary activity). However, summary-level uncertainty tends to refer to a blanket approach of applying uncertainty across a range of tasks (sometimes across a sub-system). This is appropriate if the basis of estimate (BOE) is bounded with parametrics (schedule estimating relationships or EV metrics such as earned-schedule)
  - ***Task Level*** is appropriate if project has a good understanding of specific activity uncertainties. The suggestion is to use some general bounds as guidelines to modify and apply to schedule activities as appropriate via a 3-point Distribution

Description	Remaining Duration	Start	Finish	Preceding Tasks	Succeeding Tasks	Uncertainty	Minimum Duration	Most Likely	Maximum Duration
Aurora Mission	**0**	**09/08/2016**			**0010;000013;00001Ⅰ**				
Instrument 1	**45**	**10/27/2016**	**12/28/2016**						
Design 1	15	10/27/2016	11/16/2016	0010;000013;000012	000004	Low	14	15	17
Build 1	25	11/17/2016	12/21/2016	000003	000005	Low	24	25	29
Test 1	3	12/22/2016	12/26/2016	000004	000006	Low	3	3	3
Pack andShip 1	2	12/27/2016	12/28/2016	000005	000015	Low	2	2	2
Instrument 2	**34**	**10/27/2016**	**12/13/2016**	**000001**					
Design 2	12	10/27/2016	11/11/2016	0010;000013;000012;	000009	High	10	12	22
Build 2	15	11/14/2016	12/02/2016	000008	000010	High	13	15	28
Test 2	5	12/05/2016	12/09/2016	000009	000011	High	4	5	9
Pack and Ship 2	2	12/12/2016	12/13/2016	000010	000015	High	2	2	4
Subsystem Development 1	25	09/08/2016	10/12/2016	000001	000003;000008	High	21	25	46
Subsystem Development 2	35	09/08/2016	10/26/2016	000001	000003;000008	Low	33	35	40
Subsystem Development 3	33	09/08/2016	10/10/2016	000001	000003;000008	Medium	30	33	51
System Integration Final Testing	**39**	**12/29/2016**	**02/21/2017**						
Integrate Systems	20	12/29/2016	01/25/2017	000011;000006	000016	Medium	18	20	31
Test System	15	01/26/2017	02/15/2017	000015	000017	Medium	14	15	23
Ship to Launch Site	4	02/16/2017	02/21/2017	000016	000018	Low	4	4	5
Facility Checks	2	02/22/2017	02/23/2017	000017	000019	Low	2	2	2
Final Alignment	6	02/24/2017	03/03/2017	000018	000020	Low	6	6	7
Launch Vehicle Integration and En...	11	03/06/2017	03/20/2017	000019	000021	Low	10	11	13
Launch Activities	8	03/21/2017	03/30/2017	000020	000023	Low	8	8	9
Launch	**0**		**03/30/2017**	**000021**					



The figure illustrates how the uncertainty will be applied to the schedule activities during the simulation.

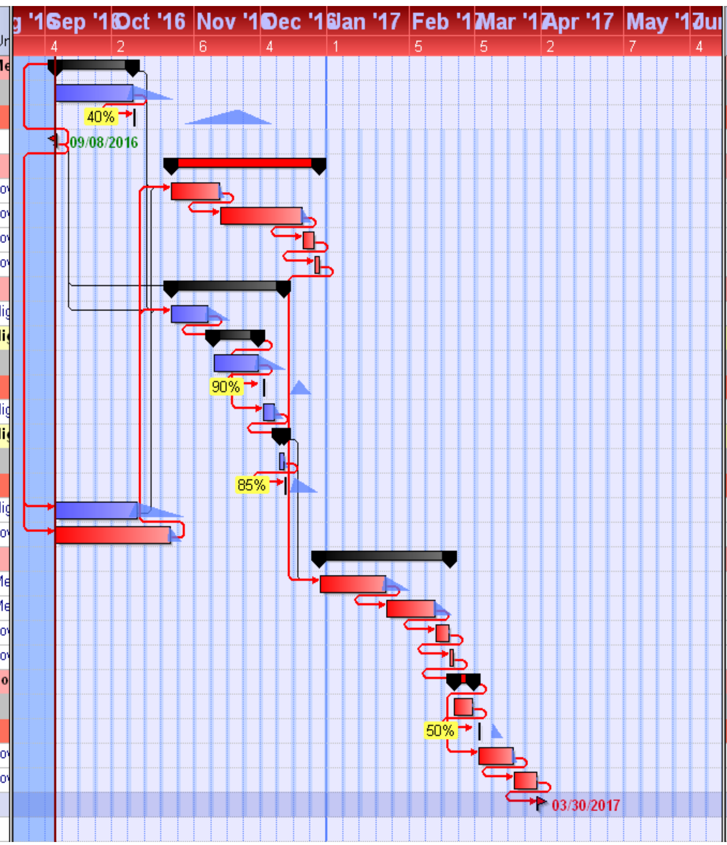
Schedule Risks

- **Risk is an event not in the project's baseline plan that has an undesirable outcome (discrete risk).**
- **The event is characterized by a probability of occurring (likelihood) and an expected impact if the event occurs (consequence).**
- **In a SRA, risk consequences are typically represented by a distribution** of pessimistic/most likely/optimistic impacts, expressed in the number of days the risk will impact the schedule.
- **The approaches for characterizing risks** for schedule risk analysis are typically based on information from **analogous missions** and **expert knowledge.**

Applying Risks

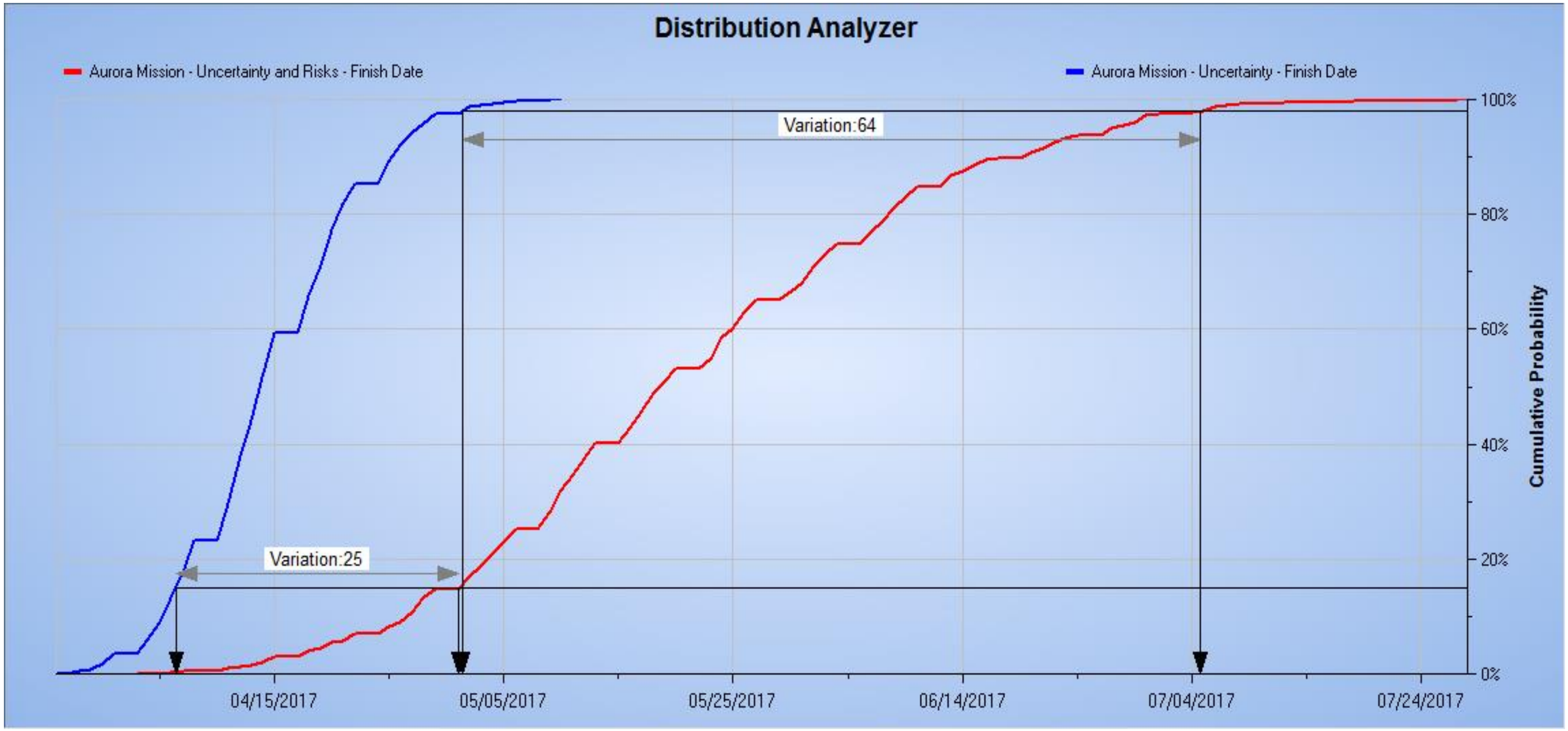
RISK	LIKELIHOOD (%)	IMPACTS (DAYS) (MIN, MOST LIKELY, MAX)	TASK MAPPING
R1: LATE INSTRUMENT 2 PROCUREMENT	90%	10, 15, 20	Build 2
R2: FINAL ALIGNMENT RISK	50%	4, 6, 10	Final Alignment
R3: SUBSYSTEM 3 TEST FAILURE	40%	20, 45, 60	Subsystem Development 2
R4: SHIPPING DELAY FOR INSTRUMENT 2	85%	2, 5, 10	Pack and Ship 2

ID	Description	Remaining Duration	Start	Finish	Preceding Tasks	Succeeding Tasks	Ur	Minimum Duration	Most Likely	Maximum Duration	Task Existence %
0010	**Subsystem Development 3**	**33**	**09/08/2016**	**10/10/2016**	**000001**	**000003;000008**	**Me**				
0010: B	Subsystem Development 3	33	09/08/2016	10/10/2016		0010:003		30	33	51	
0010:00	Subsystem 3 Failure	0	10/11/2016	10/10/2016	0010: B			20	45	60	40%
000001	**Aurora Mission**	**0**	**09/08/2016**			**0010;000013;00001**					
000002	**Instrument 1**	**45**	**10/27/2016**	**12/28/2016**							
000003	Design 1	15	10/27/2016	11/16/2016	0010;000013;000012	000004	Lo	14	15	17	
000004	Build 1	25	11/17/2016	12/21/2016	000003	000005	Lo	24	25	29	
000005	Test 1	3	12/22/2016	12/26/2016	000004	000006	Lo	3	3	3	
000006	Pack andShip 1	2	12/27/2016	12/28/2016	000005	000015	Lo	2	2	2	
000007	**Instrument 2**	**34**	**10/27/2016**	**12/13/2016**	**000001**						
000008	Design 2	12	10/27/2016	11/11/2016	0010;000013;000012;	000009	Hi	10	12	22	
000009	**Build 2**	**15**	**11/14/2016**	**12/02/2016**	**000008**	**000010**	**Hi**				
00000	Build 2	15	11/14/2016	12/02/2016		000009:001		13	15	28	
00000	Late Instrument 2 Procurement	0	12/05/2016	12/02/2016	000009: B			10	15	20	90%
000010	Test 2	5	12/05/2016	12/09/2016	000009	000011	Hi	4	5	9	
000011	**Pack and Ship 2**	**2**	**12/12/2016**	**12/13/2016**	**000010**	**000015**	**Hi**				
000011	Pack and Ship 2	2	12/12/2016	12/13/2016		000011:004		2	2	4	
000011	Shipping Delay for Instrument 2	0	12/14/2016	12/13/2016	000011: B			2	5	15	85%
000012	Subsystem Development 1	25	09/08/2016	10/12/2016	000001	000003;000008	Hi	21	25	46	
000013	Subsystem Development 2	35	09/08/2016	10/26/2016	000001	000003;000008	Lo	33	35	40	
000014	**System Integration Final Testing**	**39**	**12/29/2016**	**02/21/2017**							
000015	Integrate Systems	20	12/29/2016	01/25/2017	000011;000006	000016	Me	18	20	31	
000016	Test System	15	01/26/2017	02/15/2017	000015	000017	Me	14	15	23	
000017	Ship to Launch Site	4	02/16/2017	02/21/2017	000016	000018	Lo	4	4	5	
000018	Facility Checks	2	02/22/2017	02/23/2017	000017	000019	Lo	2	2	2	
000019	**Final Alignment**	**6**	**02/24/2017**	**03/03/2017**	**000018**	**000020**	**Lo**				
000019:	Final Alignment	6	02/24/2017	03/03/2017		000019:002		6	6	7	
000019:I	Final Alignment Risk	0	03/06/2017	03/03/2017	000019: B			4	6	10	50%
000020	Launch Vehicle Integration and En...	11	03/06/2017	03/20/2017	000019	000021	Lo	10	11	13	
000021	Launch Activities	8	03/21/2017	03/30/2017	000020	000023	Lo	8	8	9	
000023	**Launch**	**0**		**03/30/2017**	**000021**						



Understanding Risk-Based Outputs

- **Because many risks can be mitigated, it is essential to carefully establish and manage margin with discrete risks in mind.**



The figure shows the difference between the uncertainty-only impacts (blue curve) and the combined effect of uncertainty and risk impacts (red curve) on the project completion Launch milestone. The confidence level of meeting the 05/01/17 launch date was close to 98% when only uncertainty was applied; however, with the inclusion of risks, the confidence level dropped to 15%. Thus, the project would have a low likelihood of meeting the planned launch date if it does not actively manage its risks.

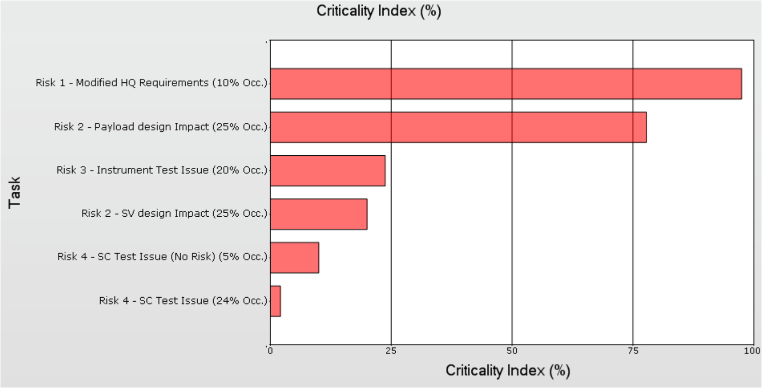
Identifying the Probabilistic Critical Path(s)

- **The SRA should be used to identify the sensitivity of the uncertainty and risks to the overall critical path calculations.**
- **An assessment of probabilistic critical paths can uncover the path with the greatest cumulative impacts from uncertainty and risks that is likely to end up as the longest path when the effort has completed.**
- **The SRA results will show the probability of tasks becoming critical path activities.**

Criticality Path				Preceding Tasks				
Name	Description	Rem D	Criticalit	Lin	Name	Description	Rem D	Criticali
000001	Aurora Mission	Mlstn	100%					
000008	Design 2	12	95.4%	FS	00000	Aurora Mission	Mlstn	100%
				FS	00001	Subsystem Development 2	35	48.7%
				FS	0010	Subsystem Development 3	33	40.3%
				FS	00001	Subsystem Development 1	25	13.7%
000009	Build 2	15	95.4%	FS	00000	Design 2	12	95.4%
000010	Test 2	5	95.4%	FS	00000	Build 2	15	95.4%
000011	Pack and Ship 2	2	95.4%	FS	00001	Test 2	5	95.4%
000015	Integrate Systems	20	100%	FS	00001	Pack and Ship 2	2	95.4%
				FS	00000	Pack andShip 1	2	5.5%
000016	Test System	15	100%	FS	00001	Integrate Systems	20	100%
000017	Ship to Launch Site	4	100%	FS	00001	Test System	15	100%
000018	Facility Checks	2	100%	FS	00001	Ship to Launch Site	4	100%
000019	Final Alignment	6	100%	FS	00001	Facility Checks	2	100%
000020	Launch Vehicle Integration and Encaps	11	100%	FS	00001	Final Alignment	6	100%
000021	Launch Activities	8	100%	FS	00002	Launch Vehicle Integration and Encaps	11	100%
000023	Launch	0	100%	FS	00002	Launch Activities	8	100%

The figure provides the critical path report after uncertainty and risks were applied. From this information, the probabilistic critical path can be better understood. Higher percentages indicate a higher likelihood of a particular task becoming critical, or in other words, ending up on the critical path. If the SRA had not been performed, then the project may not have known that the tasks associated with Instrument 2 (Build 2, Test 2, Pack and Ship 2) are likely to be critical due to uncertainty and risks. The project may also not have realized that Subsystem 2 and Subsystem 3 are very close in criticality due to uncertainty and risks.

Understanding the Probabilistic Critical Path(s)



- **In many instances, the inclusion of uncertainty and risks may change the likely critical path to something other than the deterministic critical path.**
- **Most schedule risk analysis software will provide supplemental** results, such as a risk tornado chart showing the order of risks that have the most impact on the total schedule duration**.**
- **The *critical activities* list should be reviewed against the deterministic critical path *and* the probabilistic critical path(s).**
  - Presuming that the "critical activities" list was taken into account as uncertainty distributions and discrete risks were defined, these tasks may be reflected in the *critical path report*.
  - Any differences between the criticality path report and the project's "critical activities" list should be reviewed so that the project can fully understand why particular items on the project's list are not showing up as critical as a result of the SRA (e.g., were the applied uncertainty bounds inadequate, or are the items really not as "critical" to the schedule as initially thought, etc.)
- **For any unexpected activities that show up on the probabilistic critical path, the network logic and durations for these activities should be reviewed to ensure that no errors were made.**
- **Performing schedule risk analysis enables the project to make risk-informed decisions concerning its most critical tasks, as well as its critical path.**

ESTABLISHING AND ALLOCATING SCHEDULE MARGIN

Once the SRA results have been considered in establishing how much schedule margin is needed for successful project completion, projects can insert margin tasks to represent the time necessary to account for estimated uncertainty and schedule risks.

Using SRA Results to Inform Margin Allocation

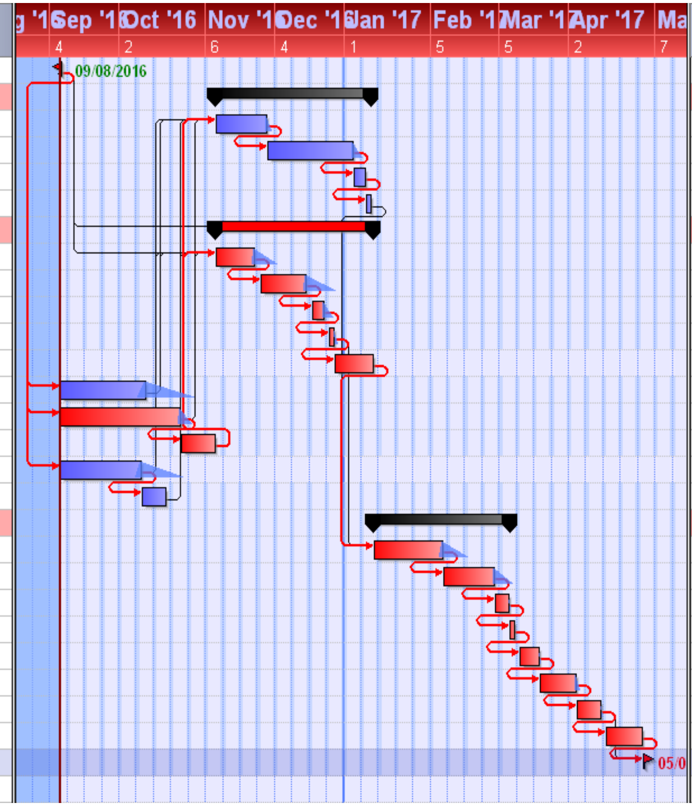
- **A probabilistic schedule risk analysis (SRA) is highly recommended as a basis for establishing the placement of adequate schedule margin.**
  - The results of the SRA may be considered along with other factors that often contribute to determining the amount of schedule margin that should be applied to a schedule, such as expert judgment or rules of thumb.
  - Appropriate margin placement should be determined through thorough analysis of the deterministic and probabilistic critical paths.
- **Schedule margin must be inserted into the schedule at strategic locations so that it satisfies its intended purpose to aid in ensuring a successful project completion and can be easily accounted for as part of the critical path sequence.**
  - Deliberate locations for margin might include placement ***along the critical path where risk impacts are expected to occur, or where mitigation activities might be planned***. *If the project has identified some other order of risk mitigation due to funding, management priorities, or other constraints, margin can be established and risks can be worked off the simulation according to management's plan.
  - It is also recommended that some margin be placed ***at the end of the schedule network logic flow just prior to the appropriate set of project completion tasks or project finish milestone***.
  - Other locations for margin might include placement ***just prior to key lifecycle milestones or reviews***.
- **Use caution when considering margin for:**
  - ***Performance Delays*** - Should performance delays occur, the project may need to work weekends or extra hours to finish on time versus using margin.
  - ***Critical Activities (not on the critical path)*** - Oftentimes, management will place margin on a path due to its sensitivity to "critical tasks". It is important to note that when smaller blocks of margin are created and associated with key events within the IMS, they may not fall on the project critical path and therefore will have no effect on the project completion date.

Office of the
Chief Financial Officer

SRA-Informed Margin Allocation

Joint Space Cost Council Scheduler's Forum

ID	Description	Remaining Duration	Start	Finish	Preceding Tasks	Succeeding Tasks	Uncertainty	Minimum Duration	Most Likely	Maximum Duration
000001	Aurora Mission	0	09/08/2016			0010;000013;00001				
000002	Instrument 1	45	11/10/2016	01/11/2017						
000003	Design 1	15	11/10/2016	11/30/2016	0060;0050;0010;0000	000004	Low	14	15	17
000004	Build 1	25	12/01/2016	01/04/2017	000003	000005	Low	24	25	29
000005	Test 1	3	01/05/2017	01/09/2017	000004	000006	Low	3	3	3
000006	Pack andShip 1	2	01/10/2017	01/11/2017	000005	000015	Low	2	2	2
000007	Instrument 2	46	11/10/2016	01/12/2017	000001					
000008	Design 2	12	11/10/2016	11/25/2016	0060;0050;0010;0000	000009	High	10	12	22
000009	Build 2	15	11/28/2016	12/16/2016	000008	000010	High	13	15	28
000010	Test 2	5	12/19/2016	12/23/2016	000009	000011	High	4	5	9
000011	Pack and Ship 2	2	12/26/2016	12/27/2016	000010	0070;000015	High	2	2	4
0070	Margin - Instrument2 (16d)	16	12/28/2016	01/12/2017	000011	000015				
000012	Subsystem Development 1	25	09/08/2016	10/12/2016	000001	000003;000008	High	21	25	46
000013	Subsystem Development 2	35	09/08/2016	10/26/2016	000001	0050;000003;00000	Low	33	35	40
0050	Margin (Buffer) - Sub2 (10d)	10	10/27/2016	11/09/2016	000013	000003;000008				
0010	Subsystem Development 3	33	09/08/2016	10/10/2016	000001	0060;000003;00000	Medium	30	33	51
0060	Margin (Buffer) - Sub3 (8d)	8	10/11/2016	10/20/2016	0010	000003;000008				
000014	System Integration Final Testing	39	01/13/2017	03/08/2017						
000015	Integrate Systems	20	01/13/2017	02/09/2017	0070;000011;000006	000016	Medium	18	20	31
000016	Test System	15	02/10/2017	03/02/2017	000015	000017	Medium	14	15	23
000017	Ship to Launch Site	4	03/03/2017	03/08/2017	000016	000018	Low	4	4	5
000018	Facility Checks	2	03/09/2017	03/10/2017	000017	000019	Low	2	2	2
000019	Final Alignment	6	03/13/2017	03/20/2017	000018	000020	Low	6	6	7
000020	Launch Vehicle Integration and En...	11	03/21/2017	04/04/2017	000019	000021	Low	10	11	13
000021	Launch Activities	8	04/05/2017	04/14/2017	000020	0020;000023	Low	8	8	9
0020	Margin - Launch Activities (11d)	11	04/17/2017	05/01/2017	000021	000023				
000023	Launch	0		05/01/2017	0020;000021					



The figure shows how margin (and buffer) tasks might be distributed in the schedule after the SRA results are considered. Instrument 2 activities are now showing up on the critical path instead of Instrument 1, which gives management proper insight into which elements in the schedule need more attention.

MANAGING THE SCHEDULE BY ESTABLISHING AND MAINTAINING RISK-INFORMED MARGIN

The project should take a proactive approach in managing the schedule by maintaining a risk-informed schedule, which includes risk-informed schedule margin.

Managing Margin When Margin Needs to be Utilized

- **Continually perform SRAs to understand and address potential risk impacts to the project throughout its lifecycle.**
- **Prioritize risks and determine appropriate handling strategies.**
  - Once the simulation is run, the project should be able to determine whether the potential impacts of the uncertainty and risks can be absorbed given the allotted margin. However, rather than waiting for the risks impacts to occur, proactive management might include adding risk mitigation activities to the schedule through the approved use of margin.
- **Follow margin processes and track margin usage.**
  - The project will need to determine trigger points at which margin should be released to manage risks. Waiting too late to use margin may result in an inefficient use of the available time (i.e the margin may not be as helpful as it could have been if released earlier).
  - When mitigation activities are added to the schedule, they become part of the project's plan, and the margin is accordingly reduced in duration to maintain the project's planned finish date.
  - It is important to note that the duration and cost of a mitigation activity may not be the same as the duration and cost of the risk impact; in most cases, it should require less money to mitigate the risk ahead of time than to recover from the risk impact(s), which is why projects should aim to mitigate risks, when possible.
  - Sometimes when a risk is mitigated, the impact is not completely reduced or some level of threat remains. These *residual risks* will need to be accounted for in the project's risk list and subsequent SRAs.

Managing Margin When Margin Does *Not* Need to be Utilized

- **Sometimes expected risk impacts do not occur, work takes place as planned, and tasks finish on time. Schedule margin (or buffers) along these "on-time" paths should not simply be wasted or consumed through waiting for the next work activity to start.**
  - ***Start subsequent activities early.*** The project should actively analyze the schedule to determine whether any subsequent activities can start earlier than planned (i.e., prior identification of early start dates may help facilitate this analysis). If tasks can start as soon as their predecessors are finished, this can save the project money by completing work sooner and perhaps gaining total slack later in the schedule to help with potential performance issues or unknown risks.
  - ***Re-shift to offset other delays in the schedule.*** The project may consider re-shifting and using the "available resources" in other under-performing areas of the schedule.
  - ***Add in previously descoped work (with appropriate approvals).***
  - ***Perform value engineering or additional testing.*** The project may consider the opportunity for certain technical elements to enhance technical performance (e.g., reliability, supportability, maintainability, survivability, etc.).
  - ***Return the margin duration to the project as float (i.e., an earlier end date).***
  - ***Move margin downstream in the workflow.***
  - ***If margin near the end of the schedule will not be needed, the project may be able to***:
    - Move up the finish milestone (i.e., deliver earlier, launch earlier, etc.). *This is likely not an option for most space flight projects.
    - Focus on completing any outstanding documentation (i.e., waivers, approvals, signatures).
    - Allow personnel some down time prior to launch activities, for example.

Managing the Need for More Margin than is Available

- **Should SRA results indicate a low confidence level or the need for margin in excess of what is planned to meet a higher confidence level, the project may need to consider viable options in modifying the project plan/schedule to regain appropriate total float, and ultimately establish adequate risk-informed margin.**
- **For example, the project may need to take into account other workflows, workarounds, or contingency options that were not previously considered to "buy back" schedule margin. Schedule workarounds may take into account viable schedule compression techniques for activities along the critical path, such as:**
  - performing tasks in parallel (fast tracking)
  - adding resources (crashing)
  - utilizing other replanning methods to capture recovery or new technical approaches
- **However, the project manager will need to weigh the potential addition of new risks to the project through these techniques.** For example, performing work in parallel may add new risks to the project, whereas adding resources could be expensive. Taking these risks and uncertainties into account in a SRA on the hypothetical, "replanned" schedule and evaluating the resulting confidence level will help the project manager to have a good grasp on whether the benefits outweigh the risks.

Monitoring, Tracking, and Controlling Margin Consumption (1 of 3)

- **Margin can be consumed by risks and uncertainties in several ways:**
  - risks become realized and slow down current work or require additional, new work
  - risk mitigations are developed and incorporated into the project plan/schedule, or
  - uncertainties become realized and slow down current work or require additional, new work
- **As margin is consumed or reallocated and critical paths change, buffer activities that were once on less-critical paths may end up on the new, primary critical path, and effectively become "margin" activities. Careful tracking of schedule margin (and buffer) consumption/reallocation and comparison to critical path total float provides an indication of schedule completion date realism.**
- **The project may have a pre-determined "planned depletion" of margin over the life cycle of the project. Analyzing the SRA results and comparing the SRA-based margin establishment/allocation to the predetermined guidelines can serve as a cross-check between the project management's initial expectations and the particular nuances of the project's risk posture. Deviations from the organization's planned depletion guidelines should be supported by the SRA results, with rationale clearly documented.**

From (point in life cycle)	To (point in life cycle)	Amount of Planned Margin
Confirmation	Beginning of Integration & Test	1 month of schedule margin per year
Integration & Test	Shipment to Launch Site	2 months of schedule margin per year
Delivery to Launch Site	Launch	1 week of schedule margin per month

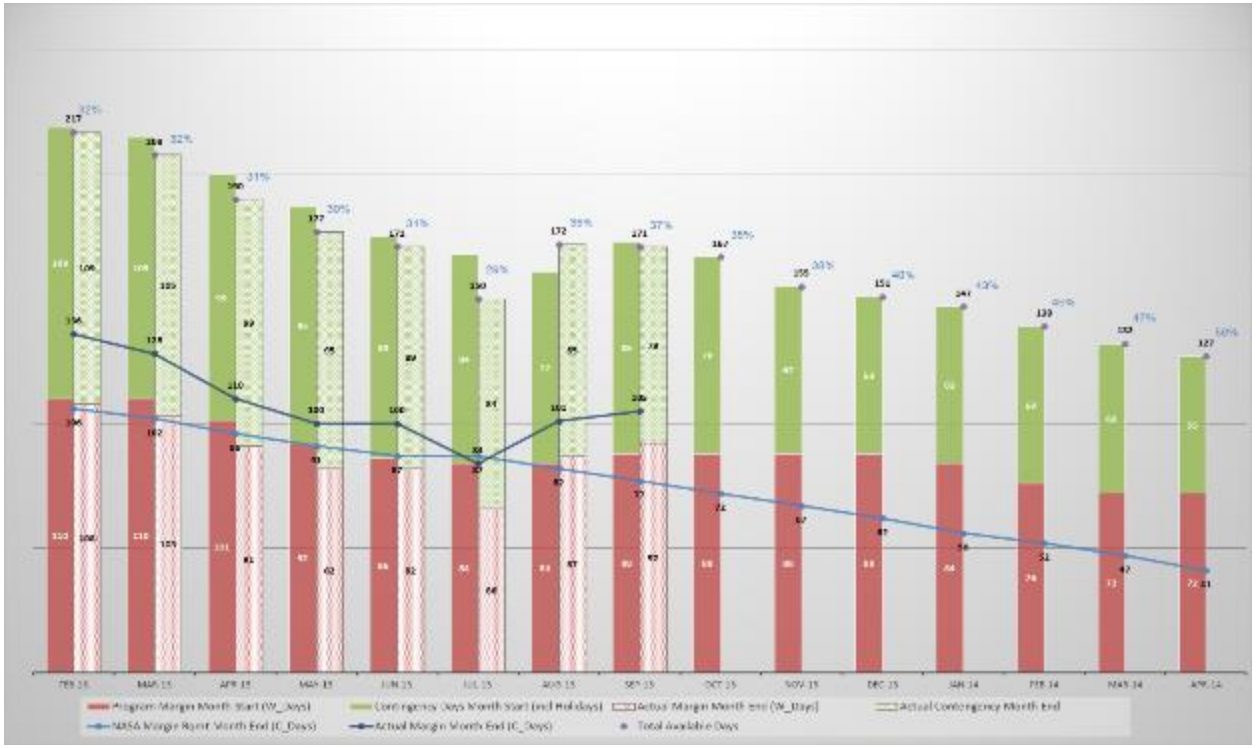
- **It is good practice to maintain a log indicating the changes in schedule margin and the reason for those changes.**

Monitoring, Tracking, and Controlling Margin Consumption (2 of 3)

- **Margin vs. Contingency.**
  - ***Margin*** – "working days" available in a schedule (where the project does not already have work defined/planned) to mitigate or absorb schedule risk
  - ***Contingency*** – "non-working days" (e.g., weekends or holidays) should only be used as a resource to the project manager to recoup delays due to poor schedule performance so as to not utilize schedule margin
  - Project management should keep in mind that contingency days will likely cost the project more money than using available float, but if there is no float available, contingency days should be the next option prior to the consideration of margin.

- **If the project monitors schedule margin in working days and contingency days separately, the project management will have a better understanding of the time resources available to the project at any given point in time.**

Monitoring, Tracking, and Controlling Margin Consumption (2 of 3)



The chart above distinguishes between margin (i.e., working days) as "W", contingency days (weekends or holidays) as "Contingency", and calendar days as "C." The solid red (margin) and green bars (contingency) are stacked to show the number of days available at a particular month's start that are not planned work days. The crosshatched red (margin) and green (contingency) bars show the actual month-end days available, with the point at the top of the bars showing the total number of month-end days available (i.e., margin + contingency). The lower blue line indicates the planned margin burn down; whereas the upper blue line indicates the actual month-end margin remaining. The percentage at the top of each set of bars shows the percentage of total days of margin and contingency available as a percentage of the days-to-go in the schedule.

CONCLUSION

This presentation provides techniques that can be employed throughout the project's life cycle, which will help to continually validate and verify allocated schedule margin based on a thorough analysis of deterministic critical path activities, as well as the schedule uncertainties and risks that may or may not be on the deterministic critical path. This more holistic approach of understanding how the project's probabilistic critical path results from the consideration of task durations and sequencing, as well as schedule risks and uncertainties at any given point in time, provides a solid basis of estimate for not only establishing and tracking margin, but for actively managing margin activities. The continual use of SRAs to risk-inform the schedule allows for risk impacts and the impacts of mitigation activities to be better understood and can aid in providing justification for project management decisions on how risks are managed and margin is allocated.

BACK-UP

Why Do We Need to Perform SRAs?

- Agency Requirements -

- **NPR 7120.5E, 2.4.3 (projects greater than $250 million)**
  - Tightly coupled and single-project programs (regardless of life-cycle cost) and projects (with an estimated life-cycle cost greater than $250 million) shall develop probabilistic analyses of cost and schedule estimates to obtain a quantitative measure of the likelihood that the estimate will be met in accordance with the following requirements.
    - "…shall provide a **range of cost and range for schedule at KDP 0/KDP, each range** (with confidence levels identified for the low and high values of the range) **established by probabilistic analysis** and based on identified resources and associated uncertainties by fiscal year."
    - "…shall develop a resource-loaded schedule **and perform a risk-informed probabilistic analysis** that produces a JCL."
- **NPR 1000.5B**
  - "Ensure acquisitions that require cost, **schedule**, and/or confidence level estimates are based on realistic estimates and achievable schedules
  - "For major acquisitions, are based on probabilistic cost and **schedule**
- **NPR 7123.1**
  - Entrance criteria for MDR/SDR "updated cost and **schedule data with ranges** and a basis of estimate"
  - Entrance criteria for PDR "Life Cycle Cost and Integrated Master Schedule (IMS) that are ready to be baselined after review comments are incorporated. When required, the Joint Confidence Level (JCL) analysis."

Why Do We Need to Perform SRAs?

- More-Informed Management Tools -

- **Durations are uncertain, but we need them to be as realistic and reliable as possible**
  - Because each activity has an uncertain duration that depends in part on uncertainties about effort and resources, the entire duration of the overall program schedule is also uncertain. (GAO)
  - Performing a schedule risk analysis requires collaboration between technical managers, risk managers and project schedulers/analysts. This collaboration process will aid in ensuring that the assigned parameters are realistic and lead to more reliable schedule risk data for making management decisions. (NASA)
  - Unless a statistical simulation is run, calculating the completion date from schedule logic and duration estimates in the schedule tends to underestimate the overall program critical path duration. (GAO)
- **We need to have a firm grasp of the project's critical path**
  - Conducting a schedule risk analysis may reveal that, with risks considered, the path most likely to delay the program is not the critical path or the longest path in the static CPM schedule. (GAO)
- **We need to understand whether the project is carrying adequate schedule margin**
  - As part of the baseline approval process, a SRA can help to ensure that there is adequate schedule margin and that it is clearly identified in the schedule. (NASA)

Management insight into the critical path is essential in making accurate resource and manpower decisions to successfully achieve project completion. Thus, it is imperative to always know what sequence of tasks is the real driver affecting project completion.